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End Effects and Load Diffusion in Composite Structures

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FINAL REPORT

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[1] Saint-Venant end effects for anisotropic materials (C. O. Horgan and L. A. Carlsson). Invited book Chapter in " Comprehensive Composite Materials ", (ed by A. Kelly and C. Zweben), Elsevier Publishers, 2000, pp. 5-21.

[2] Equilibrium solutions for compressible nonlinearly elastic materials (C. O. Horgan). Invited Chapter in *Nonlinear Elasticity: Theory and Applications* (ed. by R. W. Ogden and Y. Fu), Cambridge University Press, 2001, pp.135-159.

[3] The stress response of functionally graded isotropic linearly elastic rotating disks (C. O. Horgan and Alice M. Chan), *J. of Elasticity* 55, 1999, 219-230.

[4] Simple torsion of isotropic hyperelastic incompressible materials with limiting chain extensibility (C. O. Horgan and G. Saccomandi), *J. of Elasticity* 56, 1999, 159-170.

[5] Saint-Venant end effects in anti-plane shear for functionally graded linearly elastic materials (C. O. Horgan and R. Quintanilla), *Mathematics and Mechanics of Solids* 6, 2001, 115-132

[6] Spatial decay of end effects in functionally graded heat conducting materials (C. O. Horgan and R. Quintanilla), *Quarterly of Applied Mathematics* 59, 2001, 529-542.

[7] Pure azimuthal shear of isotropic, hyperelastic incompressible materials with limiting chain extensibility (C. O. Horgan and G. Saccomandi), *International J. of Nonlinear Mechanics* 36, 2001, 465-476.

[8] Large deformations of a rotating solid cylinder for non-Gaussian isotropic, incompressible hyperelastic materials (C. O. Horgan and G. Saccomandi), *J. of Applied Mechanics* 68, 2001, 115-117.

[9] Anti-plane shear deformations for non-Gaussian isotropic, incompressible hyperelastic materials (C. O. Horgan and G. Saccomandi), *Proceedings of the Royal Society of London,*

Series A, 457, 2001, 1999-2017.

8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED

C. O. Horgan, (PI); D. Galic (MS May 2002)

9. REPORT OF INVENTIONS (BY TITLE ONLY):
None

NASA Contact

(1) Continued close contact maintained with Dr. J. Starnes and Dr. M. Nemeth, NASA.

(2) Letters and reprints sent to several NASA personnel.

(3) Extensive contact with Prof. Daniel Inman, Director, Center for Intelligent Material Systems and Structures, Virginia Tech on potential applications of the work to smart structures technology. Prof. Horgan presented a seminar at Virginia Tech which has led to sustained interaction between their research groups. The importance of end effects in smart structural damping problems e.g. layered beams and plates with viscoelastic, metallic and PZT components is currently under investigation and promises to have a major impact on NASA technology.

Technology Transfer

The results of this research are being widely utilized in the technical literature on composite materials, with technology transfer to such areas as composite design and materials testing. The attached summary of technology transfer to the Boeing Commercial Airplane Group attests to the applicability of the results. Dr. Horgan visited the Boeing Company in Seattle on May 25, 1995 to further this important area of technology transfer. He presented a 1-hour lecture entitled "End Effects in Composite Structures" to the Boeing group. This interaction continues. Further contact with Boeing personnel was made at the 4th International Conference on Sandwich Construction, Stockholm, Sweden in June 1998. Interaction with Dr. Tom Bitzer, Hexcel Corporation, also took place at this meeting. Dr. Bitzer is chair of the ASTM Committee on Testing of Composites. Dr. Horgan has also initiated joint work with Professor Leif Carlsson of Florida Atlantic University on the role of end effects in composite testing. Professor Carlsson visited the University of Virginia and presented a seminar on issues in composite testing. Professors Horgan and Carlsson have co-authored an invited book chapter in the 6 volume " Comprehensive Composite Materials" (ed. by A. Kelly and C. Zweben), Elsevier Publishers , 2000, pp. 5-21.This book series reviews the developments in composites technology in the 20th century and sets the stage for future work.

Statement of the Problems Studied and Results

The research carried out here builds on our previous NASA supported research on the general topic of *edge effects and load diffusion* in composite structures. Further fundamental solid mechanics studies were carried out to provide a basis for assessing the complicated modeling necessary for large scale structures used by NASA. An understanding of the fundamental mechanisms of load diffusion in composite subcomponents is essential in developing primary composite structures. Specific problems recently considered were focussed on end effects in sandwich structures and for functionally graded materials. Both linear and nonlinear (geometric and material) problems have been addressed. Our goal is the development of readily applicable design formulas for the decay lengths in terms of non-dimensional material and geometric parameters. Analytical models of load diffusion behavior are extremely valuable in building an intuitive base for developing refined modeling strategies and assessing results from finite element analyses. The decay behavior of stresses and other field quantities provides a significant aid towards this process. The analysis is also amenable to parameter study with a large parameter space and should be useful in structural tailoring studies.

The research carried out here is concerned with the general issues of *local gradients, discontinuities* and *load diffusion* in composite structures. Fundamental solid mechanics studies are carried out to provide a basis for assessing the complicated modeling necessary for the large scale structures used by NASA. An understanding of the fundamental mechanisms and nature of load diffusion in composite subcomponents is essential in the development of primary composite structures, for example, the diffusion of wingbox loads into the composite fuselage shell wall of the proposed high-speed civil transport aircraft or the diffusion of internal loads around major discontinuities in stiffened fuselage shells such as passenger doors. (Results in this area are particularly relevant to the NASA Airframe Structural Integrity Program). Special purpose analytical models of load diffusion behavior are extremely valuable in building an intuitive base for developing refined modeling strategies and assessing results from general purpose finite element analyses. For example, a rational basis is needed in choosing where to use three-dimensional to two-dimensional transition finite elements in analyzing stiffened plates and shells. The decay behavior of stresses and other field quantities furnished by the research carried out here provides a significant aid towards this element transition issue. A priori knowledge of the extent of boundary-layers induced by edge effects (e.g. bending boundary layers) is also useful in determination of the instrumentation location in structural verification tests or in material characterization tests. The analysis is also amenable to parameter study with a large parameter space and should be useful in structural tailoring studies.

The particular problem area investigated is that of local gradients, discontinuities and load diffusion in anisotropic and composite structures. In the application of elasticity theory to problems of practical interest, an essential simplification is made by ignoring local gradients or discontinuities through consideration of load resultants. For example, the theories for strength of materials, involving beams, plates and shells have such relaxed boundary conditions as cornerstones of their development. The justification for such approximations is usually based on some form of Saint-Venant's principle characterizing the boundary layer behavior involved. Thus, Saint-Venant's principle is appealed to in neglecting *local gradients* and *discontinuities*, and experience with homogeneous *isotropic* materials (e.g., metals) in linear elasticity has served to establish this standard procedure. It lies at the very foundations of applied structural analysis as practiced in the aerospace industry. Saint-Venant's principle also is the fundamental basis for static mechanical tests of material properties. Thus property measurements are made in a suitable *gage section* where *uniform* stress and strain states are induced and local effects due to clamping of the specimen are neglected on invoking Saint-Venant's principle. Such traditional applications of Saint-Venant's principle require major modifications when strongly anisotropic and composite materials are of concern. For such materials, local stress effects persist over distances *far greater* than is typical for isotropic metals. The implications of such extended end zones due to anisotropy are far reaching in the proper analysis and design of structures using advanced composite materials.

Several developments of our earlier work have been made recently under NASA support. We have made substantial progress in understanding the extent of end effects in sandwich structures. In Figure 1 attached, a symmetric sandwich strip in anti-plane shear (Mode III) is depicted schematically together with an asymptotic formula (*) for the decay length. This result provides an estimate for a scaled decay length for the case when the core is much more compliant than the face sheets. The graphs in Fig. 2, 3 show how useful the result (*) is from a design viewpoint. The results were extended to include the effect of imperfect interface bonding. It was shown that imperfect interface bonding leads to much slower decay of end effects than in the perfectly bonded case. Applications of the results for the perfectly bonded case have been made to configurations used by the Boeing Company in the Boeing/NASA Advanced Technology Composite Aircraft Structures (ATCAS) Program. See the discussions in [1].

We have also made considerable recent progress in investigation of end effects in functionally graded materials (FGMs). Such materials are now used in a variety of applications e.g. to provide superior oxidation and thermal shock resistances. Thermal residual stresses can be relaxed in metal-ceramic layered materials by inserting a functionally graded interface layer betweeen the metal and the ceramic. It is shown in [5] that the inhomogeneity can enhance or inhibit load diffusion. In a recent paper [6], similar results on spatial decay of transient end effects in heat-conducting FGMs have been obtained. These results are of importance to the NASA mission in view of the widespread use of FGMs in NASA applications. The stress response of rotating disks composed of FGMS is analyzed in [3], while in [8] large deformations for rubber-like rotating cylinders are considered. The papers [2,4, 7, 9] are concerned with both geometric and material nonlinearities.

Edge Effects in Composite Structures

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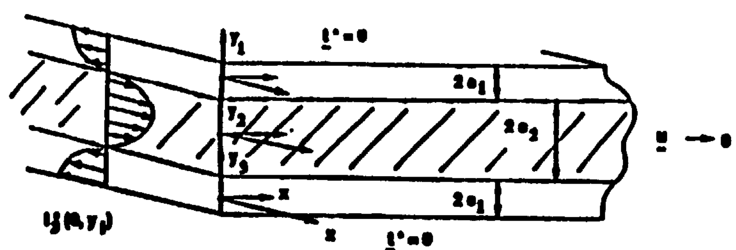
(*) $\boxed{\bar{d} \sim \ln(100)\,[\delta f(1-f)]^{1/2} \quad \text{as } \delta \to \infty}$

Assumptions

I. Sandwich Structures

- Anti-plane shear (Mode III)
- Linear elasticity (Isotropic phases)

$$\delta = \frac{\mu_1}{\mu_2},\ f = \text{volume fraction},\ \bar{d} = \text{decay length} = \frac{d}{2c_1+c_2}$$



Results

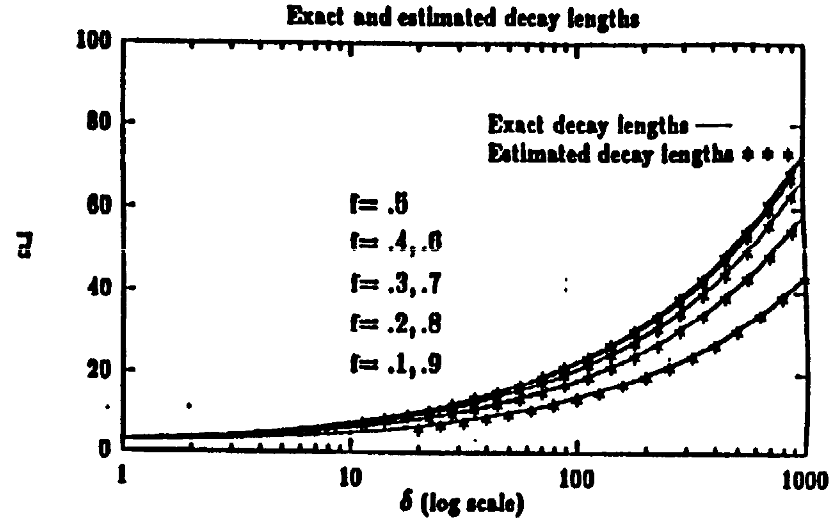


Fig. 2. Scaled decay length vs. δ, for various f

$\left(f = \frac{2c_1}{2c_1+c_2},\ \delta = \mu_1/\mu_2 \right)$

Decay length for semi-infinite sandwich strips subjected to self-equilibrated end loads.

The characteristic decay length (i.e., the distance over which end effects decay to 1% of their end values) versus a nondimensional material parameter (the ratio of face to core shear modulus) is plotted in Fig. 2. In Fig. 3, the plot is for varying volume fraction and fixed δ. The decay length is seen to be *smallest* for a homogeneous isotropic material, $\delta = 1$, as shown in Fig. 2. This decay length is approximately equal to the width of the strip. From Fig. 3, the decay length for fixed δ, is seen to be *largest* at a volume fraction f=.5. These figures (and the associated asymptotic formulas) can be used directly in the design process for sandwich structures.

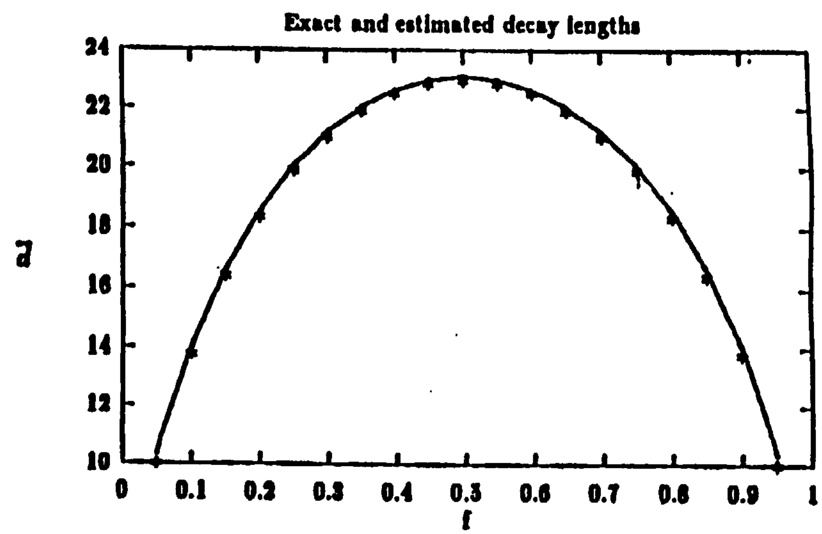


Fig. 3. Scaled decay length vs. volume fraction ($\delta = 100$)

Statement of the Impact of the Proposed Research

The research program being carried out here contributes to NASA's Structural Mechanics Program in several ways. At the outset it has two important impacts. Firstly, we continue to show from specific problems, simple enough to be amenable to considerable analysis yet elaborate enough to be of practical significance, that end and edge effects in anisotropic, laminated, materials and structures are far more severe than in homogeneous isotropic structures of the same geometry and under the same loads. Secondly, it shows that *elementary* (classical) theories of beams, plates, and shells, *properly supplemented and iterated,* suffice for the accurate determination of stresses in thin-walled, layered structures, even in the presence of strong end or edge effects. Thus, an important impact of this research is to convince users of large structural computer codes that the underlying equations must be examined carefully to make sure, on the one hand, that they properly and accurately incorporate end and edge effects, and, on the other, that they are not unnecessarily elaborate (i.e., incorporate effects of the same order as others they tacitly neglect.) It is also anticipated that new design results will continue to be developed which will be of immediate use to composite designers in particular in connection with *material tailoring.*

A further contribution of the work is in the area of *large deformations* of composite materials. As is well known, consideration of both geometric and material nonlinearities in composites often leads to striking differences from predictions of corresponding linear theories. In view of the rapid utilization of advanced composite materials in current NASA technology, studies on large deformations of such materials promise to have a widespread impact on the NASA research mission.

The research should also assist in the development of new structural concepts, using composite materials, for application to primary aircraft structures. The analysis is amenable to parametric studies of value in structural tailoring. Analytic results of the type sought here are crucial complements to large scale computational analyses of actual aircraft and space structures that often have several local gradients and discontinuities involving load diffusion.

A Technology Transfer Example

A Boeing/NASA Advanced Technology Composite Aircraft Structures (ATCAS) Program has been active since 1989. The primary objective of this program is to:

> "Develop an integrated technology (manufacturing & structures) and demonstrate a confidence level that permits cost-and weight-effective use of advanced composite materials in primary structures of aircraft with the emphasis on pressurized fuselages."

In this program, a section of a widebody aircraft (244" dia) just aft of the wing/body intersection is being analyzed by the Boeing Commercial Airplane Group in Seattle, Washington. Sandwich structures are being used for the side and keel of this section. The particular structures consist of Hercules' AS4/8552 for the skin and Hexcel's HRP honeycomb core (see next page for details on layup etc.). Compression testing of laminate coupons indicate the need to incorporate Saint-Venant end effects in interpretation of the test data. The work of the PI's is being utilized in this effort. One of the P.I's (C. O. H.) visited the Boeing Group in Seattle on July 1, 1994 and on June 1/2, 1995 to consolidate this interaction. Collaborative research with the Boeing scientists (Dr. W. A. Avery, coordinator) is being initiated. One objective is to develop a systematic testing program to be carried out by Integrated Technologies, Inc. (Intec), Bothell, WA, under subcontract to Boeing. Preliminary tests by Intec have indicated problems due to end effects in the sandwich panels under investigation. It is anticipated that the results obtained in our research program will have direct application to these problems. In fact, the interaction with the Boeing/Intec mechanics and materials group is providing additional motivation and stimulus to our efforts in understanding the extent of Saint-Venant end effects in advanced composite materials and structures.

Table 1 Material Types

Panel ID	Skin Material	Form	No of Plies	Nominal Ply Thickness *(in)*	Layup ID	Core Type	Core Thick-ness *(in)*
AK7	8-256	Tow	12	0.0080	Keel 1	HRP-3/16-8.0	0.75
AK8	8-256	Tow	12	0.0080	Keel 1	HRP-3/16-8.0 & TPC-3/16/5.5	0.75
AK10a	AS4/8552	Tape	12	0.0073	Keel 1	HRP-3/16-8.0	0.75
AK10b	AS4/8552	Tape	12	0.0073	Keel 3	HRP-3/16-8.0	0.75
AK10c	AS4/8552	Tow	12	0.0073	Keel 1	HRP-3/16-8.0	0.75
AK10d	AS4/8552	Tow	12	0.0073	Keel 1/ Keel 3	HRP-3/16-8.0	0.75

Table 2 Layups

Layup ID	Number of Plies	Ply Orientation
Keel 1	12	[45/0/-45/90/0/-45/45/0/90/-45/0/45]
Keel 3	12	[30/-30/0/90/0/-45/45/0/90/0/-30/30]

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